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CONTROLS ON SUSPENDED-SEDIMENT TRANSFER AT A HIGH-ARCTIC GLACIER, DETERMINED FROM STATISTICAL MODELLING

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ABSTRACT

Simple linear regression models have been widely employed in the analysis of suspended-sediment concentration (SSC) time series from glacierized catchments, although they have many limitations. This paper builds regression models which address these shortcomings and permit inferences concerning the controls on suspended-sediment transfer from a glacier at 78°N in the Svalvard archipelago. A bivariate regression model, deterministically predicting SSC from discharge alone, explained less than 15 per cent of the variance in SSC. A multivariate model, incorporating additional potentially explanatory variables, offered little improvement. Diurnal hysteresis in the data gives rise to quasi-autocorrelation in the residual series from regression models. This was effectively removed by incorporating dummy diurnal variables into the multivariate model. The presence of a first-order autoregressive, stochastic process gives rise to true autocorrelation in the residual series from regression models. This was accommodated by incorporating an ARIMA (1,0,0) term into a multivariate autoregression model. The model-building process yielded a systematic progression in the explanation of variance in SSC, stripping away pattern in the autocorrelation function of the residual series; mean model error was reduced from 54 per cent to 6 per cent. The dependence of SSC on the magnitude of discharge is weak and highly variable, whereas the dependence of current SSC on recent values of SSC, revealed through the stochastic term, is an order of magnitude greater and relatively constant during the melt season. The dominant control on SSC throughout the melt season is therefore short-term sediment availability. The simple and largely unchanging stochastic process generally responsible for generating the observed SSC series implies a simple and unchanging glacier drainage system. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS suspended sediment; Arctic; regression; time series; hysteresis; autocorrelation

INTRODUCTION

Suspended-sediment transport modelling in glacierized catchments

Models of suspended-sediment transport in proglacial streams have previously been developed in order to forecast sediment yields for engineering purposes (e.g. Østrem, 1975; Bezinge, 1987; Bezinge *et al.*, 1989; Bogen, 1989), to predict erosion rates for geomorphological purposes (e.g. Fahnestock, 1963; Mathews, 1964; Collins, 1979; Metcalf, 1979), to investigate fluvial processes (e.g. Church and Gilbert, 1975; Hammer and Smith, 1983; Gurnell and Fenn, 1984; Richards, 1984) and to identify and interpret seasonal changes in suspended-sediment transport from glacierized catchments (e.g. Collins, 1989, 1990; Gurnell *et al.*, 1992a, 1994; Hodgkins, 1996).

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By far the most common model is a rating curve derived from ordinary least-squares (OLS) linear regression of suspended-sediment concentration (SSC), or sometimes (perhaps spuriously) suspended-sediment load, against discharge (e.g. Østrem, 1975; Collins, 1979; Parks and Madison, 1984; Repp, 1988). The popularity of the rating curve stems from its simplicity of construction and interpretation, and from the way in which SSC is deterministically predicted from discharge. However, the relationship between discharge and SSC is far from simple in reality. Accordingly, the performance of rating curves is frequently poor. For instance, Parks and Madison (1984) derived rating curves for glacierized basins in Alaska that had standard errors ranging from –50 to 100 per cent, whereas Fenn (1989) found that rating curves developed for one season's data from the Glacier de Tsidjiore Nouve basin in Switzerland predicted suspended loads from 34 to 278 per cent of measured values when applied beyond that season. Østrem (1975) considered that the relationship between discharge and suspended-sediment transport changed 'more or less continuously' within and between seasons.

Fenn *et al.* (1985) summarized the effects which limit the applicability and accuracy of suspended-sediment rating curves as follows.

1. Variations in sediment supply at the seasonal scale, such as may arise from early-season flushing (Liestøl, 1967; Collins, 1988, 1989), late season exhaustion (Østrem, 1975; Gurnell *et al.*, 1992a), or increasing sediment supply (Gurnell *et al.*, 1994; Hodgkins, 1996).
2. Variations in sediment supply at the diurnal scale, between the rising and falling limbs of the hydrograph, leading to diurnal hysteresis (Østrem *et al.*, 1967; Collins, 1979; Richards, 1984; Hodgkins, 1996). This represents a particular problem for forecasting SSC from discharge alone, since there are, in effect, two values of SSC for each value of discharge: one for the rising and one for the falling limbs of the hydrograph.
3. Transient SSC pulses which are independent of discharge (Bogen, 1980; Gurnell, 1982; Gurnell and Warburton, 1990).
4. Entrainment and deposition of sediment in the proglacial region (Mills, 1979; Bogen, 1980; Hammer and Smith, 1983; Richards, 1984), even in the absence of proglacial lakes (Church and Gilbert, 1975).
5. Variations in sediment supply associated with rainfall-induced events (Church, 1972; Richards, 1984).

The inadequacy of the rating curve is usually reflected in the presence of autocorrelation in the residual series. 'Quasi-autocorrelation' results from shortcomings in the formulation of the model: non-linearity, omission of relevant independent variables, the presence of response lags/leads, and hysteresis at different time scales (Fenn *et al.*, 1985). 'True-autocorrelation', however, indicates that the SSC series is generated not through a linear dependence on discharge, yielding mutually independent values, but by a *stochastic* process in which the present value of SSC is a probabilistic function of previous values of SSC and of present and previous random disturbances, such that successive values in the series are not independent (Richards, 1979; Fenn *et al.*, 1985).

Gurnell and Fenn (1984) turned autocorrelation to advantage by estimating a Box–Jenkins transfer function (Box and Jenkins, 1976) between discharge and SSC series from Glacier de Tsidjiore Nouve. Univariate autoregressive integrated moving average (ARIMA) stochastic time-series models of discharge and SSC series were developed for an estimation period, and the simple transfer function used to bring them into phase and apply a scaling factor. Noise from the function was satisfactorily modelled using the residual from the previous hour's prediction. Predictions from the transfer function model were far superior to those from rating curves, such that Gurnell and Fenn (1984) recommended a similar approach be used whenever possible. Fenn (1989) found that a transfer function model gave predictions of suspended-sediment load (SSL) from 96 to 105 per cent of measured values at Glacier de Tsidjiore Nouve, even when applied beyond the season in which it was developed. Nevertheless, despite the demonstrable superiority of the transfer function approach in forecasting SSC, it has not been widely adopted, because it requires a detailed series of uniformly spaced observations for estimation, and such series are even now rarely available in practice.

Attempts to improve the performance of the rating curve have frequently involved subdividing the discharge and SSC records into shorter intervals of more uniform response for which a linear

relationship may be valid, or at least less invalid. Collins (1979) estimated rating curves for individual rising and falling limbs of the diurnal hydrograph at Gornergletscher, Switzerland. Hammer and Smith (1983) derived early and late season rating curves for the proglacial stream of Hilda Glacier, Alberta, Canada. Richards (1984) obtained separate rating curves for periods of meltwater runoff and storm runoff at Storbreen, Jotunheimen, Norway. Gurnell *et al.* (1992a) divided discharge and SSC time series from Haut Glacier d'Arolla, Valais, Switzerland, into five subperiods on the basis of variations in diurnal maximum and minimum discharge, prior to estimating regression (and also ARIMA and transfer function) models.

An alternative approach has been to develop multivariate rating curves incorporating additional explanatory variables which may represent components of variability at different temporal scales. Richards (1984) introduced the rate of change of discharge per hour, positive during rising stage and negative during falling stage, into a multivariate rating curve to represent diurnal hysteresis. It was found that this variable was the main control on variation in SSC during periods of meltwater runoff. Willis *et al.* (1996) found that the variables discharge, rate of change of discharge and days since discharge was equalled or exceeded were all significant in a multivariate rating curve, although the improvement over a rating curve using discharge alone was slight, and the residuals were autocorrelated.

Aims and methods

This paper has two related aims. By analysing a proglacial SSC time series with a range of regression models, it is intended to:

1. Identify what forms of regression model most successfully account for variance in the series, taking into account problematic effects such as hysteresis and true-autocorrelation.
2. Infer physical controls on the variation in SSC, from interpretation of the parameters of models most successful in describing the series.

The method is to follow a procedure in which models of increasing complexity are constructed, accounting for successively greater proportions of the variation in SSC. At each stage, attention is directed towards the residuals from the model to indicate any non-random pattern which remains. Starting with a simple OLS linear regression model, in which discharge is the only independent variable, additional predictor variables, representing various sediment supply processes, are introduced into a multiple-regression model. Dummy diurnal variables are then introduced so as to account for the diurnal hysteresis which is typically problematic when attempting to predict SSC from rating curves. Finally, a stochastic component is introduced, which uses antecedent values of SSC and current random disturbances to model current SSC.

In order to assess the performance of each model, the following are plotted: the observed and predicted series, the residual series, and the variation of the residuals with predicted values of SSC, discharge and daily hour (Figures 5–9). The autocorrelation function (ACF) for the residual series from each model is also shown (Figure 10), to indicate how successful each model is at representing the observed pattern in SSC; were the model completely successful, this would be in the form of 'white noise' (purely random disturbances about zero). By introducing diurnal and stochastic components into regression models, it is intended to bridge the gap between simple but inadequate regression models and effective but complex time-series models. The iterative model-building approach, by which the analysis passes from model to residual series to new model, is intended to facilitate interpretation of the models and their parameters, by directing specific model components to specific features of the residual series. The statistical analyses described in this paper were all conducted using the 'correlation and regression' and 'time-series analysis' modules of the SPSS software package.

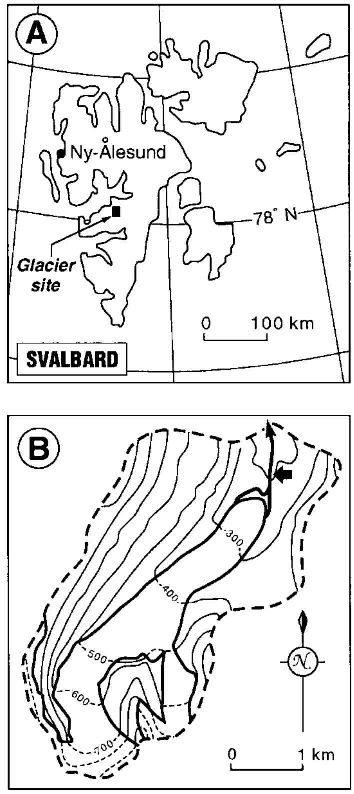

Figure 1. (A) Location of Scott Turnerbreen within the Svalbard archipelago. (B) The Scott Turnerbreen catchment. Contours are in m a.s.l. Solid, bold lines at the glacier snout indicate principal runoff routes. The arrow indicates the location of the proglacial stream gauging and sampling site

SITE DESCRIPTION

Scott Turnerbreen is a 3·3 km^2 glacier, of altitude range 230–680ml a.s.l., located in central Spitsbergen (78°06′N, 15°57′E), occupying a catchment of total area 12·8 km^2 (Figure 1). The catchment geology is dominated by gently dipping Tertiary sandstones, shales and siltstones (Major and Nagy, 1972). Basal temperatures measured in boreholes (Hodgkins, 1994) were –4·1 °C (surface altitude 305 m a.s.l., 42 m ice depth) and –3·3 °C (surface altitude 595 m a.s.l., 54 m ice depth). The observed temperature gradients indicate that pressure-melting requires ice thickness of at least 95 m. It is therefore unlikely that the glacier bed is temperate even at its deepest point, 76 m.

Drainage of meltwater from Scott Turnerbreen is dominated by two channels located at its east and west margins, capturing supraglacial runoff (Figure 1). The east channel carries *c.* 80 per cent of the total discharge. The course of the channels is through moraine, ice-cored moraine and stagnant ice at the glacier margins; they have the characteristics of subaerial channels, though in places they flow beneath the glacier margins. There are no moulins directing meltwater subglacially. Both streams debouch from the glacier margin in the proglacial region, upvalley of a prominent end moraine, from which the glacier has retreated since the 1930s. The east stream issues over a winter proglacial icing (*aufeis* or *naled*), which accumulates over winter in the basin between the glacier terminus and the end moraine (Hodgkins *et al.*, 1998). The west stream flows across an area of moraine before reaching its confluence with the east system inside the end moraine. The proglacial stream below the confluence directly breaches the end moraine before flowing down the main valley floodplain, across which it braids extensively.

DATA COLLECTION

A record of SSC was obtained by discrete sampling in a stable, unbraided reach of the proglacial stream (Figure 1). SSC measurements span the interval 21 July to 15 August 1992. SSC is given in units of kg m^{-3} (equivalent to $g\,l^{-1}$), for consistency with the units of discharge, $m^3 s^{-1}$.

Water samples were obtained automatically with an Epic Products' 1011 portable sampler. A control tube in the sample chamber gives sample volume repeatability to within ±0·0005 1, and the volume of samples collected was 0·5 1. The sampling interval varied between 0·5 and 3·0h according to the frequency with which samples could be processed. Samples were filtered in a perspex pressure-filtration apparatus, using pre-weighed Whatman grade 40 fast-filtration paper, which has an initial penetration pore size of 8 μm, although as the paper rapidly clogs, the effective pore size is reduced during filtration (Gurnell, 1987). The filter papers were returned to the UK at the end of the field season, for drying and reweighing in order to determine SSC.

Gurnell *et al.* (1992b) have assessed the reliability and representativeness of similar SSC-monitoring programmes in proglacial streams. They found that point samples from a pump sampler provided unbiased estimates of SSC by comparison with a depth-integrating sampler in the same location, although the variability of estimates was relatively high. Furthermore, no systematic variation in SSC was found in the cross-section of a turbulent stream away from the banks. The variation that was observed was essentially random, and therefore sampling at a fixed point would provide an unbiased estimate of SSC in the section. According to these results, the sampling programme at the Scott Turnerbreen proglacial stream should have yielded representative samples.

The accuracy of the SSC determinations is affected by four factors:

1. Variation in the water sample volume: this amounts to ±0·10 per cent.
2. Precision of the analytical balance used to weight the papers, which is ±0·0001 g: since each paper is weighed twice, this corresponds to an error of ±0·02 per cent at mean SSC.
3. Absorption of moisture by the chosen filter paper, which is hygroscopic. This could be reduced by the use of a finer pore-sized cellulose nitrate filter membrane, but this would have increased the amount of time required to filter each sample beyond practicality. From data in Gurnell *et al.* (1992b), the error from this source can be estimated as ±0·16 per cent of the mean SSC.
4. Loss of sub-8 μm particles, resulting from the use of fast-filtration paper. The exact magnitude of this error will depend upon the grain-size distribution of the suspended sediment, which is unknown in this case. However, this is not believed to be a significant problem because rapid clogging of the paper occurred, and visual inspection of the filtrate indicated no observable turbidity. Assuming that the magnitude of this error is similar to that detected by Gurnell *et al.* (1992b), it is likely that there is a *c.* 1 per cent underestimation at the mean SSC. This is therefore the greatest source of error overall.

Stage was recorded hourly, in the same reach as SSC, with a Sandhurst Technology LH-177 pressure transducer and Grant Instruments SQ32 data logger. The resulting time series was calibrated by means of linear regression with discrete discharge measurements obtained by the relative dilution technique. The substance diluted was 5g Rhodamine B fluorescent dye in 1l of streamwater. The dye was detected by continuous-flow fluorometry with a Turner Designs Model 10 fluorometer. The accuracy of the stage–discharge relationship, estimated from the standard error of the estimate, is ±13 per cent.

RESULTS

The proglacial discharge and SSC time series are shown in Figure 2, and a descriptive statistical summary is given in Table I. SSL is the product of SSC and discharge, and gives the mass of sediment transported by the proglacial stream in unit time, with the units kg s^{-1}; for daily totals this figure is very high and units of $t\,d^{-1}$ are used. Daily total SSLs , found by integrating SSL values over successive 24 h intervals, are shown in Table I.

The quantity of sediment leaving the catchment in suspension fluctuates widely, with daily total loads

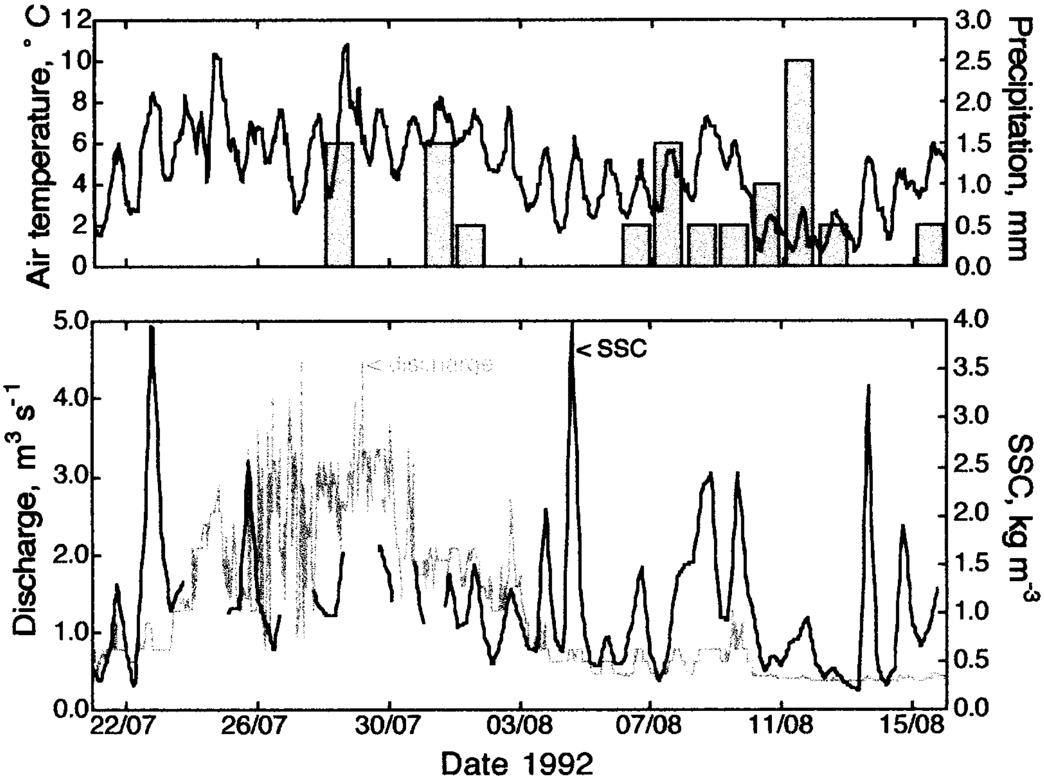

Figure 2. Basic data obtained at Scott Turnerbreen: hourly air temperature (at the proglacial stream gauging site), daily total rainfall, proglacial discharge and SSC time series

Table I. A descriptive statistical summary of the proglacial fluvial suspended-sediment transport time series

Statistic	Hourly data		Daily data,
	Concentration ($kg\,m^{-3}$)	Load ($kg\,s^{-1}$)	Load
Minimum	0·20	0·06	12
Maximum	6·05	6·86	459
Mean	1·34	1·22	126
Standard deviation	0·91	1·19	114
n	207	200	23*

* Number of days with sufficient data for daily total estimates

varying between 12 and 459 t, respectively representing 0·4 and 16 per cent of the measured total, each in 4 per cent of the time interval. This reflects a considerable range of temporal variations in the pattern of suspended-sediment transport (Figure 2), including a diurnal cycle (throughout), high-magnitude pulses (e.g. 22 July and 4 August), medium-term shifts (e.g. an increase over 7–10 August) and longer-term trends in base SSC levels (e.g. a decline over 28 July–7 August). To some extent these variations follow the pattern of meltwater discharge, especially over longer time intervals; e.g. the decline in base SSC level over 28 July–7 August, which occurs during a period of declining proglacial discharge. However, there is clearly a significant component of discharge-independent behaviour, which increases at shorter time scales; e.g. the 22 July and 4 August pulses, which both last around 3 h and are not reflected in the proglacial discharge record.

SUSPENDED-SEDIMENT TRANSFER MODELS

Data transformation

Valid linear regression models not only require the relationship between independent and dependent variables to be monotonically linear, but also to yield residuals which are normally distributed and homoscedastic with zero mean, and which are not autocorrelated; a further requirement of multiple linear regression models is that collinearity amongst independent variables is absent (Ferguson, 1977; Johnston, 1978). Some transformation of the original data is frequently necessary in order that at least some of these requirements are satisfied, and simple (and hence readily interpreted) models thereby retained. The most widely applied transformation involves taking common logarithms of both discharge and SSC data (e.g. Church and Gilbert, 1975; Richards, 1984; Gurnell, 1987). Nevertheless, Fenn *et al.* (1985) recommend careful assessment of the most appropriate transformation in all cases, rather than the uncritical application of a log–log transform.

A Box–Cox procedure (Box and Cox, 1964) was therefore employed in order to determine a transformation for the discharge and SSC datasets which would yield the most monotonically linear bivariate scatter, and regression models in which the residuals would as nearly as possible satisfy the requirements discussed above. The Box–Cox procedure defines a series of power transformations

$$i^{(\Lambda)} = (i^{\Lambda}-1)/\Lambda \qquad \Lambda \neq 0 \tag{1a}$$

$$i^{(\Lambda)} = \log_{10} i \qquad \Lambda = 0 \tag{1b}$$

where superscript Λ denotes the power transformation operator and i is an observation in a series which is replaced by $i^{(\Lambda)}$ for different values of Λ (Haworth and Vincent, 1982). This procedure has previously been shown to be appropriate for proglacial discharge and SSC data (e.g. Gurnell and Fenn, 1984; Fenn *et al.*, 1985; Fenn, 1989; Willis *et al.*, 1996). The common logarithmic transformation, corresponding to $\Lambda = 0$, yields the most normally distributed data, with minimized skewness, kurtosis and variance. The results are given in Figure 3, which shows the frequency distributions of the untransformed and transformed datasets, and the observed and fitted normal probabilities of the transformed datasets. However, the Kolmogorov–Smirnov goodness-of-fit statistic, D (the maximum absolute difference between observed and theoretical, in this case normal, cumulative probability distributions), while reduced, is not significant for either transformed dataset ($p = 0{\cdot}05$), showing that the distributions of the transformed data remain significantly different from normal. Figure 4 gives the bivariate scatter plots of the untransformed and transformed discharge and SSC data.

Deterministic models, 1: bivariate OLS linear regression

Simple OLS linear regression with $\log_{10} SSC$ as the dependent variable and $\log_{10}$ discharge, $\log_{10} Q$, as the independent variable yielded the following equation (model Bi-OLS):

$$\begin{array}{lll} \log_{10} SSC_t = & 0{\cdot}381 \log_{10} Q_t + & 0{\cdot}103 + 0{\cdot}260 \\ & 5{\cdot}929 & 4{\cdot}829 \\ & (0{\cdot}000) & (0{\cdot}000) \\ & 0{\cdot}064 & 0{\cdot}021 \end{array} \tag{2}$$

with a correlation coefficient of 0·388 and an adjusted determination coefficient of 0·146, the F-statistic being 35·153 ($p = 0{\cdot}000$). At the end of this and subsequent equations, the standard error is given as an error term, and the T-statistic (with its probability in parentheses) and the standard error are respectively stated beneath each coefficient or constant.

The explanatory power of this model is not very high, and would certainly not be acceptable for forecasting. The model conspicuously fails to reproduce the cycles in the SSC series (Figure 5A), which is

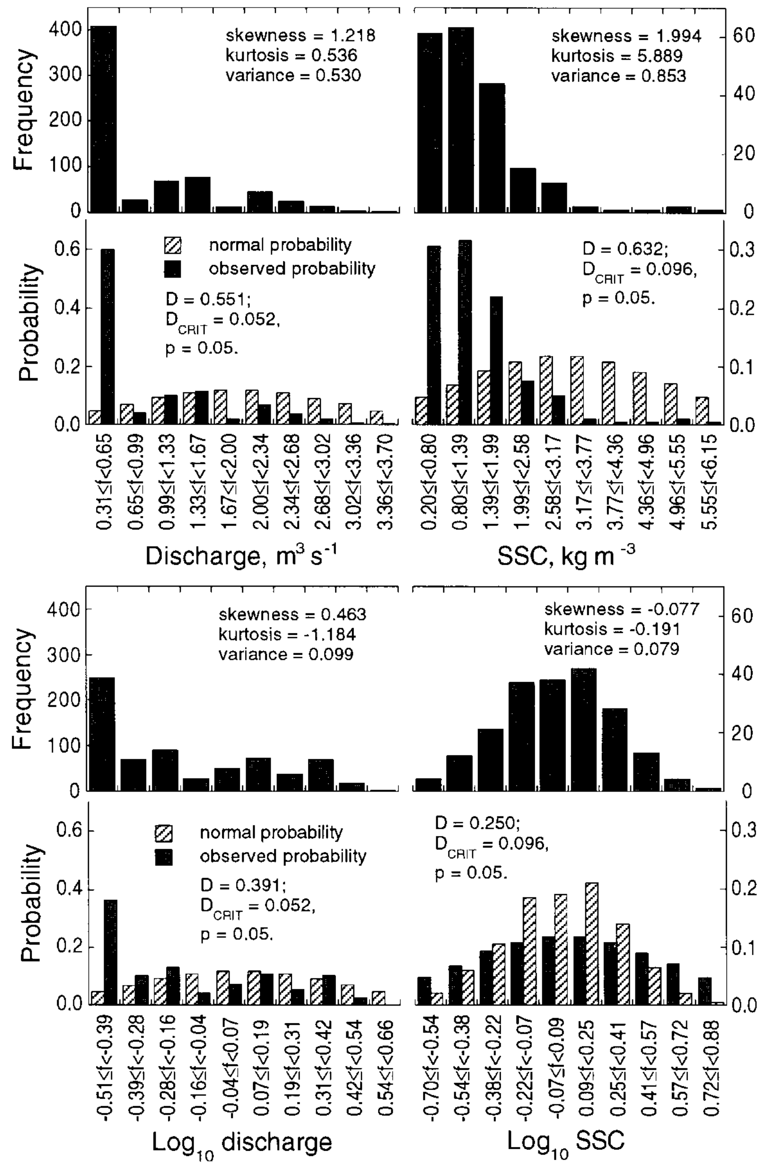

Figure 3. Frequency distributions, and the observed and fitted normal probability distributions, of the untransformed and log-transformed discharge and SSC data sets. D_{CRIT} (the critical value of the Kolmogorov–Smirnov goodness-of-fit statistic) $= 1{\cdot}36/n_{0{\cdot}5}$ ($p = 0{\cdot}05$). The null hypothesis, that the sample is drawn from a population possessing the specified theoretical distribution, is rejected if $D > D_{CRIT}$

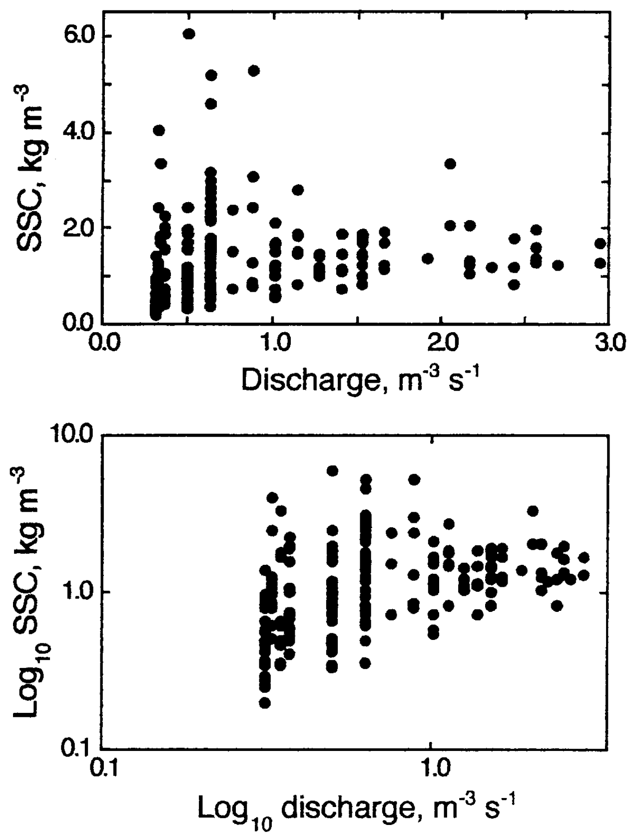

Figure 4. Untransformed and log-transformed bivariate discharge–SSC scatter plots

reflected in the strong resemblance of the residual series to the original data (Figure 5B), indicating that very little of the variance in SSC has been accounted for. In statistical terms, the residuals from the model are heteroscedastic: they exhibit less scatter at high predicted values (Figure 5C) and high discharges (Figure 5D), and also appear to follow a marked diurnal pattern, with large negative residuals in mid-morning and large positive residuals in mid-afternoon (Figure 5E).

Deterministic models, 2: multivariate OLS linear regression

If discharge alone is not an effective predictor of SSC, the incorporation of additional variables may improve the performance of the regression model. A shortcoming of the rating curve is that it effectively assumes that SSC is controlled solely by the transport capacity of the proglacial stream, whereas in reality this is less important than processes of sediment supply and storage (Richards, 1982). The following additional, independent variables were therefore specified:

1. The rate of change of discharge per hour, ΔQ, was obtained by substracting previous values of discharge from current ones, and is thus positive during rising and negative during falling stages. ΔQ varies between –2·192 and +2·707m s^{-1}. Liestøl (1967) suggested that SSC was more dependent on the rate of change of discharge than on its magnitude; similarly, Richards (1984) found that during 'non-stormflow' periods, SSC was actually not dependent on discharge, but rather on its rate of change. Liestøl (1967) explained this effect by suggesting that the rate of production of sediment by

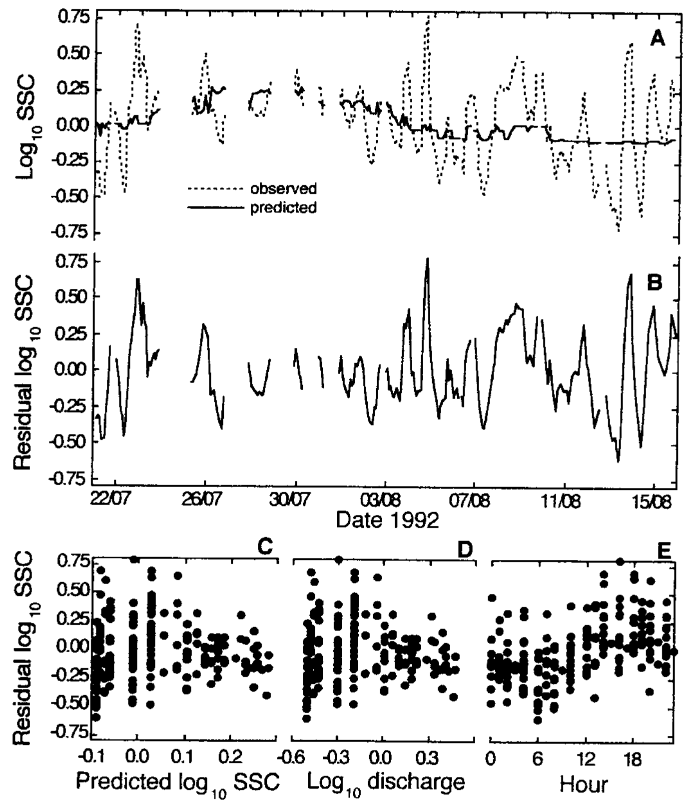

Figure 5. Model Bi-OLS results (Equation 2). (A) Observed and predicted $\log_{10}SSC$ time series. (B) Residual $\log_{10}SSC$ time series. Scatter of residual $\log_{10}SSC$ with (C) predicted $\log_{10}SSC$, (D) $\log_{10}Q$ and (E) daily hour

abrasion at the base of the glacier is relatively constant, and that during rising discharge, streams are able to tap sediment produced since the previous equivalent discharge. Hence SSC is dependent on the new area covered by streams per unit time, the rate of increase of discharge and the length of time since water last covered the area.

2. Liestøl's (1967) explanation indicates another potentially significant variable, the period of time since discharge was equalled or exceeded (Q_E), to represent the tapping of previously unworked areas of sediment by expanding streams. Q_E is defined by comparing the current value of discharge to all previous values since the start of the monitoring period, and varies between 1 and 141h. Meltwater is not routed subglacially at Scott Turnerbreen (Hodgkins, 1998; Hodgkins *et al.*, 1998). Nevertheless, the sediment supply mechanisms outlined have analogues in subaerial streams. Richards (1984) found that the total SSL of streams draining the snout of Storbreen was approximately five times that observed at the proglacial monitoring station some 1200m downstream, indicating that there was substantial storage of sediment in the proglacial region. This sediment was subsequently evacuated during periods of storm runoff, such that sediment yield to the proglacial stream was discontinuous. This mechanism is therefore analogous to that which Liestøl (1967) proposed, with the exception that sediment is stored proglacially instead of subglacially.
3. Richards' (1984) explanation, in turn, indicates another potentially significant variable – rainfall. Following Willis *et al.* (1996), four variables are specified: the amount of rain falling during the previous 1, 2, 4 and 6h, denoted R_1, R_2, R_4 and R_6 respectively. Richards (1984) suggested that during periods of rainfall, the proglacial discharge and SSL are augmented by runoff from surrounding

slopes and the proglacial region, since mountainous glacierized catchments typically show a rapid hydrological response in the presence of readily available sediment supplies. Rainfall variables are determined from meteorological data collected by an automatic weather station 500m southeast of Scott Turnerbreen at an elevation of 400m a.s.l. The maximum rainfall in the previous 1, 2, 4 and 6h is 1·0, 1·5, 1·5, and 1·5mm, respectively.

4. A final variable, hours since the beginning of the record (*H*), was included to represent sediment supply variations at the seasonal scale, including the progressive exhaustion of sediment sources by an integrating and stabilizing drainage system (Østrem, 1975; Hammer and Smith, 1983; Gurnell *et al.*, 1992a), but also the progressive increase in the area of sediment available for mass-wasting and fluvial transport as snow retreats from the proglacial region and subsequently upglacier (Gurnell *et al.*, 1994; Hodgkins, 1996). The total length of the SSC record is 618h.

The independent variables $\log_{10} Q$, ΔQ, Q_E, H and R_1, R_2, R_4 and R_6 were therefore entered stepwise into a multiple-regression model, yielding the following equation (model Multi-OLS):

$$
\begin{array}{lllll}
\log_{10}SSC_t = & 0{\cdot}421\ \log_{10}Q_t & +\ 0{\cdot}005Q_E & -0{\cdot}183\Delta Q & +\ 0{\cdot}102 \pm 0{\cdot}252 \\
 & 6{\cdot}448 & 2{\cdot}870 & -2{\cdot}575 & 4{\cdot}614 \\
 & (0{\cdot}000) & (0{\cdot}005) & (0{\cdot}011) & (0{\cdot}000) \\
 & 0{\cdot}065 & 0{\cdot}002 & 0{\cdot}071 & 0{\cdot}022
\end{array} \qquad (3)
$$

with a correlation coefficient of 0·450, and an adjusted determination coefficient of 0·190, the *F*-statistic being 16·197 ($p = 0{\cdot}000$). Despite the incorporation of ΔQ and Q_E, the improvement over the previous model is slight: only an additional 4·4 per cent of the variance in $\log_{10}$ *SSC* is explained. Neither *H* nor any of the rainfall variables were significant ($p = 0{\cdot}05$).

A potentially interesting result is that ΔQ is negatively correlated with $\log_{10}$ *SSC*. This would tend to suggest that suspended-sediment transport is greatest on the limbs of the diurnal hydrograph (ΔQ can be negative or positive) and smallest at its inflections, when stream discharge is changing most rapidly. However, the *T*-statistic and its probability indicate that ΔQ enters relatively weakly into the regression relationship, so one must be wary of attaching much importance to this result. That *H* is not significant is consistent with previous results from glaciers of similar, non-temperate thermal structure in Svalbard, indicating an overall absence of significant seasonal limitations on sediment supply (Repp, 1988; Gurnell *et al.*, 1994; Hodgkins, 1996). Conversely, as previous analyses of these data have demonstrated a strong trend towards increasing availability of sediment for fluvial transport (Hodgkins, 1996), it is possible that the linear variable *H* is not an adequate analogue for seasonal sediment supply variation. That none of the rainfall variables is significant is not entirely surprising, given the infrequency and low intensity of rainfall in the Scott Turnerbreen catchment (Figure 2), but this does, for example, indicate a very different sediment supply regime from that identified by Richards (1984). Figure 6A shows that a small number of the SSC peaks are better represented by the multivariate model than by the bivariate model (e.g. 26 July and 16 August), but that overall there is little change in the form of the residual series (Figure 6B) or in the residual scatter plots (Figure 6C–E). Similarly, Figure 10 shows that there is no significant alteration in the form of the ACF of the residual series. Accordingly, Table II indicates little change in the magnitude of the model errors.

Deterministic models, 3: diurnal multivariate OLS linear regression (accounting for diurnal hysteresis)

Autocorrelation persists in the residual series from the bivariate and multivariate OLS linear regression models (Figure 10). It should be questioned whether this is quasi- or true-autocorrelation. The transformations identified in this paper represent the most linear form of the bivariate discharge–SSC distribution so that linearity problems can be discounted as a cause of autocorrelation. A range of additional explanatory variables has been incorporated into model Multi-OLS, not all of which were significant, so that autocorrelation arising from the omission of relevant predictor variables is unlikely. The occurrence of lagged responses between discharge and SSC is discounted on the evidence of cross-

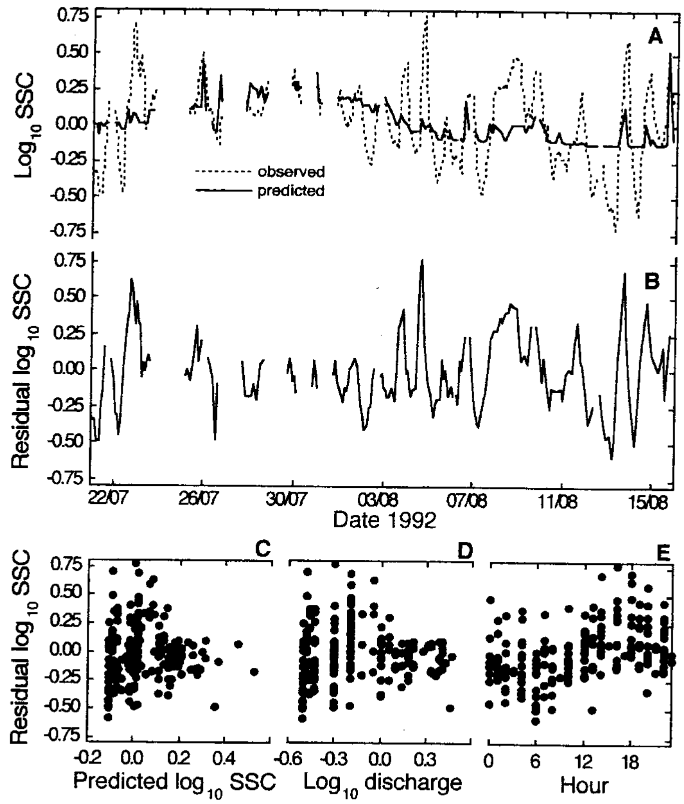

Figure 6. Model Multi-OLS results (Equation 3). (A) Observed and predicted $\log_{10}SSC$ time series. (B) Residual $\log_{10}SSC$ time series. Scatter of residual $\log_{10}SSC$ with (C) predicted $\log_{10}SSC$, (D) $\log_{10}Q$ and (E) daily hour

Table II. Residual statistics from the SSC models

Model	n/degrees of freedom	Mean absoolute error	Mean percentage error	SSE	MSE	RMS
Bi-OLS	200/198	0.204	–54.119	13.346	0.067	0.260
Multi-OLS	197/191	0.195	–77.033	12.357	0.065	0.254
Multi-OLS_{24}	200/186	0.167	12.509	8.594	0.046	0.215
AR1-ML	197/192	0.120	–5.360	4.730	0.025	0.157
AR1-ML_{24}	200/188	0.100	6.155	3.361	0.018	0.134

SSE, sum of squared errors; MSE, mean squared error; RMS, root mean squared error. These statistics refer to log-transformed data

correlation functions which indicate that there is no clearly defined, lagged, best-match position between the two variables (Hodgkins, 1994). It is, however, known that diurnal hysteresis occurs within the data, so some autocorrelation may arise from this source (Hodgkins, 1996). Seasonal hysteresis is discounted because of the lack of seasonal limitations to sediment supply (Hodgkins, 1996). The diurnal effect is very clear in the scatter plots of residuals with daily hour (Figure 5E and 6E) and in the residual ACFs (Figure 10), which display a distinctive cycle with a 24h period.

A simple but effective means of removing the effects of diurnal hysteresis from the residual series is

employed: dummy diurnal variables. In this context, the statistical 'season' is a 24 h period, i.e. a diurnal cycle; the resolution of the data is 1 h, giving 24 hourly variables. A total of 23 new variables are therefore created, t_0 to t_{22}, each taking the value 1 or 0 depending on the hour to which the equation is applied. In practice, no information is gained from using the 24th variable that could not already have been gained from the others. Each dummy diurnal variable represents observations taken at a particular time of day, which, as has been seen above, may be biased by the effects of diurnal hysteresis. These variables are used as interaction terms, assessing their impact on the slope (rather than the intercept) of the regression. The new variables were entered stepwise into a multiple regression model, with the significant variables from model Multi-OLS, yielding the following equation (model Multi-OLS$_{24}$):

$$
\begin{array}{lcccccccccc}
\log_{10}SSC = (0{\cdot}352 & -\,0{\cdot}198t_6 & -\,0{\cdot}154t_8 & +\,0{\cdot}319t_{14} & +\,0{\cdot}339t_{18} & +\,0{\cdot}271t_{16} & +\,0{\cdot}274t_{19} & +\,0{\cdot}218t_{20} & +\,0{\cdot}154t_{22} & +\,0{\cdot}131t_{12})\log_{10}Q_t \\
\quad 6{\cdot}472 & -3{\cdot}108 & -2{\cdot}322 & 4{\cdot}874 & 4{\cdot}749 & 4{\cdot}120 & 3{\cdot}655 & 3{\cdot}193 & 2{\cdot}577 & 2{\cdot}062 \\
\quad (0{\cdot}000) & (0{\cdot}002) & (0{\cdot}021) & (0{\cdot}000) & (0{\cdot}000) & (0{\cdot}000) & (0{\cdot}000) & (0{\cdot}002) & (0{\cdot}011) & (0{\cdot}041) \\
\quad 0{\cdot}054 & 0{\cdot}064 & 0{\cdot}066 & 0{\cdot}066 & 0{\cdot}071 & 0{\cdot}066 & 0{\cdot}075 & 0{\cdot}068 & 0{\cdot}060 & 0{\cdot}063
\end{array}
\qquad (4)
$$

(constant not significant) with a correlation coefficient of 0·672 and an adjusted determination coefficient of 0·422, the F-statistic being 15·335 ($p = 0{\cdot}000$). The results of this model are shown in Figure 7, from which it is clear that it is in all respects a substantial improvement over the previous models. ΔQ and Q_E are not significant in the new model, but some nine of the dummy diurnal variables are, which is reflected in the more effective representation of diurnal cycles in predicted $\log_{10}$ SSC (Figure 7A). The intercept of the regression relationship remains fixed, but the slope changes during the diurnal cycle. In effect, the dummy diurnal variable is a linear correction to the slope of the regression equation. There is a 23·2 per cent improvement in explained variance, considerable improvements in all measures of error in the residual series (Table II), and all residual scatter plots are more homoscedastic, particularly for predicted values of $\log_{10}$ SSC (Figure 7C) and daily hour (Figure 7C). Figure 10 shows that the diurnal pattern has been removed from the residual ACF.

A clear advantage of the dummy diurnal variable regression technique is that it can be applied 'blind' to any dataset without the need for it to be subdivided into intervals of apparently constant response, such as rising and falling hydrograph limbs (e.g. Collins, 1979). A single model is therefore obtained for the entire dataset, with the effects of diurnal hysteresis removed. No prior knowledge of the data is required, and though numerous new variables are incorporated into the model, these are simple to define. Nevertheless, since some autocorrelation clearly remains in the residual series from the model at short lags (Figure 10), it is concluded that this is true-autocorrelation. As long as this persists, regression models are, in a strict statistical sense, unsatisfactory, although they may be considered adequate for general prediction. A technique is required which can accommodate the autocorrelation structure inherent within the SSC data.

Deterministic-stochastic models, 1: multivariate autoregression (accounting for true-autocorrelation)

A stochastic process clearly needs to be invoked if the autocorrelation within the residual series is to be removed. ACFs which exhibit an approximately exponential decline at short lags tend to indicate the presence of an ARIMA (1, 0, 0), a first-order autoregressive, process (Box and Jenkins, 1976), i.e. a lagged regression of a series on itself, $x_t = \phi x_{t-1} + \varepsilon_t$, where x_t is the value of a series at time t, ϕ is a constant and ε is a random component (Richards, 1979). 'Autoregression' is a technique which estimates unbiased regression coefficients from series with first-order autoregressive residuals (SPSS Inc., 1988). An autoregression model was estimated using an iterative exact maximum-likelihood (ML) algorithm, with a recursive Kalman filter algorithm for imbedded missing data (Kohn and Ansley, 1986). Initially, the significant independent variables from model Multi-OLS were entered, and the following equation resulted (model AR1-ML):

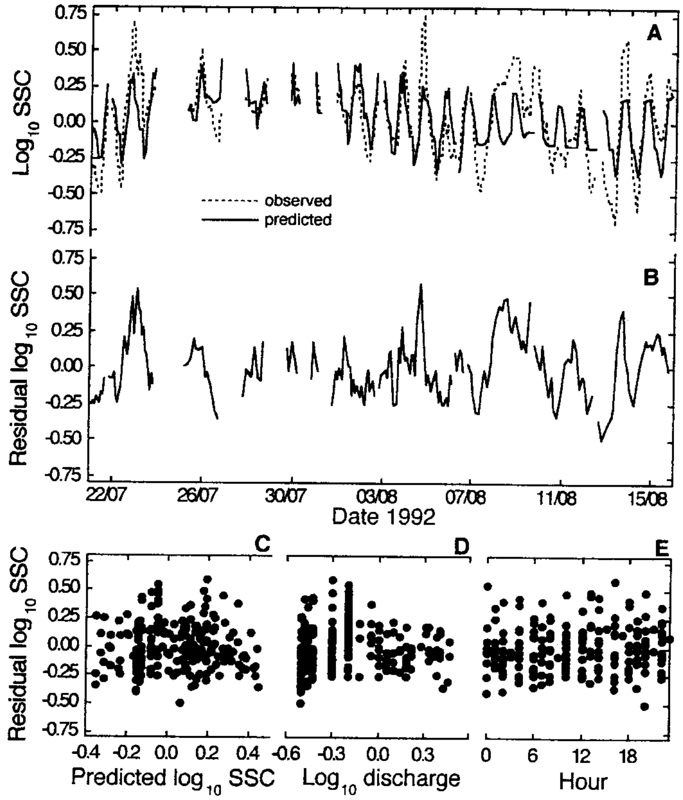

Figure 7. Model Multi-OLS_{24} results (Equation 4). (A) Observed and predicted $\log_{10}SSC$ time series. (B) Residual $\log_{10}SSC$ time series. Scatter of residual $\log_{10}SSC$ with (C) predicted $\log_{10}SSC$, (D) $\log_{10}Q$ and (E) daily hour

$$
\begin{array}{lllll}
\log_{10}SSC_t = \varepsilon_t + 0.909 \log_{10}SSC_{t-1} & + 0.432 \log_{10}Q_t & + 0.002QE & + 0.111 \pm 0.105 & \quad (5) \\
\quad 68.810 & \quad 3.792 & \quad 2.532 & \quad 2.216 & \\
\quad (0.000) & \quad (0.000) & \quad (0.012) & \quad (0.028) & \\
\quad 0.013 & \quad 0.114 & \quad 0.001 & \quad 0.050 &
\end{array}
$$

with a log-likelihood of 50·064, an Akaike Information Criterion (*AIC*) statistic of –90·129 (Akaike, 1974) and a Schwartz Bayesian Criterion (*SBC*) statistic of –73·713 (Schwartz, 1978). ΔQ was not significant at $p = 0{\cdot}05$. ε represents a random disturbance (white noise). The greater the log-likelihood and the smaller the *AIC* and *SBC* statistics, the better the model fits the data, allowing for the number of parameters.

Figure 8A and B shows, respectively, that the fit of the predicted series from this model to the data, and the resemblance of the resulting residual series to white noise, are the best obtained so far. Accordingly, there are considerable improvements in the model standard error (a 50·9 per cent reduction) and residual error statistics by comparison with model Multi-OLS_{24} (Table II). The *T*-statistic of the autoregressive parameter is an order of magnitude greater than that of any other coefficient (Equation 5), indicating that this is the dominant component of the model. The effectiveness of what is essentially a rather simple stochastic model, in fitting a complex time-series, would tend to suggest that the physical basis of the model, incorporating antecedent values of SSC and a random component, is sound (cf. Fenn, 1989). Figure 10 shows that the short-lag autocorrelation that persisted with the OLS

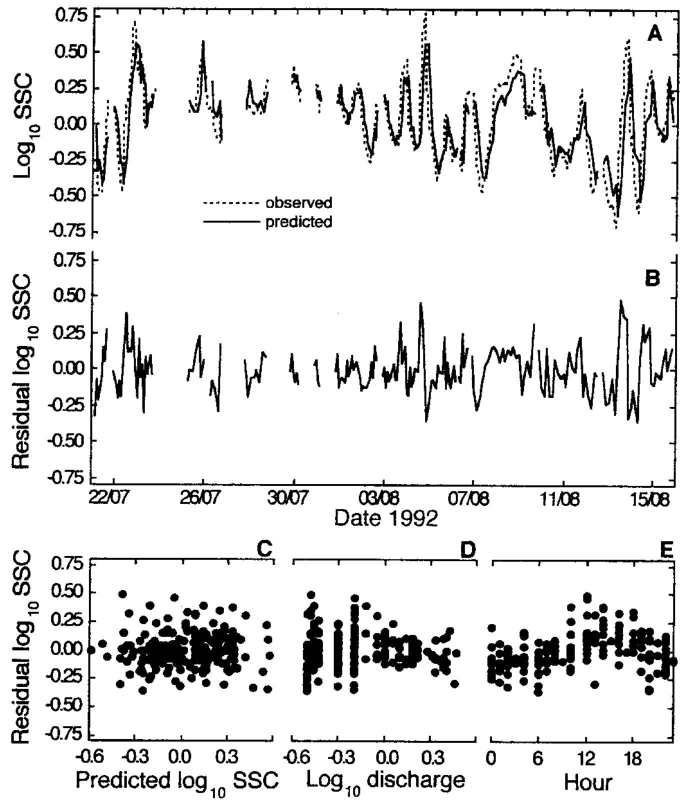

Figure 8. Model AR1-ML results (Equation 5). (A) Observed and predicted $\log_{10}SSC$ time series. (B) Residual $\log_{10}SSC$ time series. Scatter of residual $\log_{10}SSC$ with (C) predicted $\log_{10}SSC$, (D) $\log_{10}Q$, and (E) daily hour

models has been removed. The diurnal autocorrelation remains, but this may be removed by incorporating dummy diurnal variables into the multivariate autoregression model (see below). An alternative would be to difference the series at the 'seasonal' interval (24h in this case), but this would require a continuous, uninterrupted sequence of observations.

Deterministic-stochastic models, 2: diurnal multivariate autoregression

In order to produce the best-fitting model with the most homoscedastic and non-autocorrelated residuals, a diurnal component was introduced into the autoregression model. The significant independent variables from model Multi-OLS_{24} were therefore entered into a new autoregression model, and the following equation resulted (model AR1-ML_{24}):

$$\begin{array}{llllllllllll}
\log_{10}SSC_t = \varepsilon_t + & 0.917 \log_{10}SSC_{t-1} + (& 0.295 + & 0.104t_{12} + & 0.246t_{14} + & 0.250t_{16} + & 0.279t_{18} + & 0.155t_{19} + & 0.201t_{20} + & 0.087t_{22} & -0.126t_6 \\
 & 71.925 & 3.105 & 3.145 & 6.330 & 6.842 & 6.398 & 3.740 & 5.086 & 2.852 & -3.991 \\
 & (0.000) & (0.002) & (0.002) & (0.000) & (0.000) & (0.000) & (0.000) & (0.000) & (0.004) & (0.000) \\
 & 0.013 & 0.095 & 0.033 & 0.039 & 0.037 & 0.044 & 0.042 & 0.040 & 0.030 & 0.031
\end{array}$$

$$\begin{array}{l}
-0.108t_8)\log_{10}Q_t \pm 0.089 \\
-3.313 \\
(0.001) \\
0.032
\end{array} \qquad (6)$$

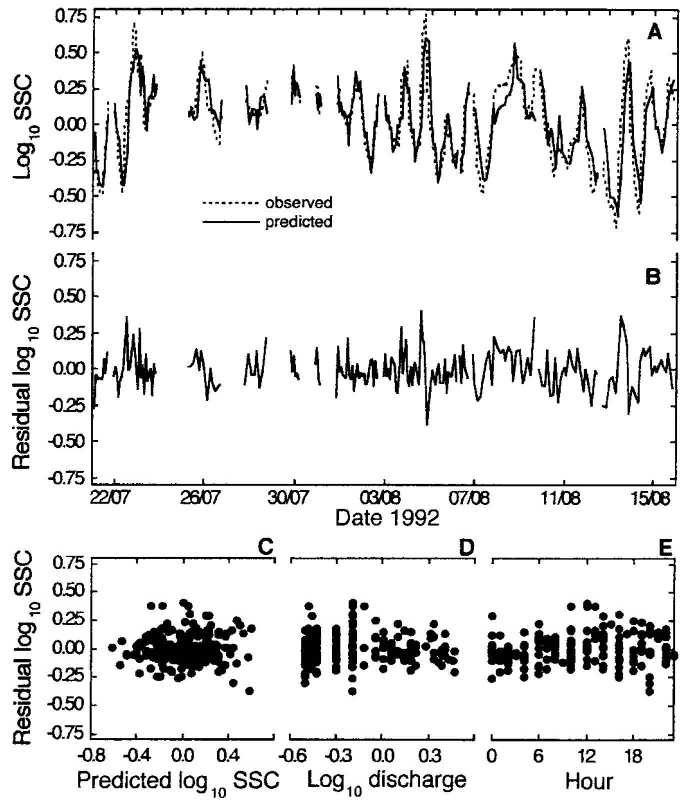

Figure 9 Model AR1-ML_{24} results (Equation 6). (A) Observed and predicted $\log_{10}SSC$ time series. (B) Residual $\log_{10}SSC$ time series. Scatter of residual $\log_{10}SSC$ with (C) predicted $\log_{10}SSC$, (D) $\log_{10}Q$ and (E) daily hour

(constant not significant) with a log-likelihood of 90·629, an *AIC* statistic of –157·258 and an *SBC* statistic of –117·678. The log-likelihood of the model is increased, relative to the non-diurnal autoregressive model, and the *AIC* and *SBC* statistics both decrease, indicating an all-round improvement in model performance. There are only small changes in the autoregression coefficients and *T*-statistics (Equation 6), compared to the non-diurnal model AR1-ML (Equation 5). Model AR1-ML_{24} offers a 15·2 per cent reduction in standard error, and similar reductions in most of the error statistics compared to previous models (Table II). The residuals from this model are approximately homoscedastically distributed with respect to predicted $\log_{10}$ *SSC* (Figure 9C), and also daily hour (Figure 9E), although there is still a hint of heteroscedasticity in the scatter of residuals with $\log_{10} Q$ (Figure 9D); nevertheless, reference back to Figure 5 (model Bi-OLS) shows how residual scatter as a whole has been reduced by the modelling procedure. There is a notable improvement in the residual ACF for model AR1-ML_{24}, which has now had both the short-lag high correlations and the diurnal correlations removed, and resembles white noise (Figure 10).

SEASONAL EVOLUTION OF SUSPENDED-SEDIMENT TRANSFER MODELS

Where physical significance can be ascribed to the parameters of statistical models, a method is available to trace changes in suspended-sediment transfer processes. Gurnell *et al.* (1994) and Hodgkins (1996) inferred seasonal changes in the processes of proglacial suspended-sediment transfer at glaciers in the Svalbard archipelago, on the basis of changes in the parameters of simple regression and time-series

models estimated for successive subperiods of the melt season. In particular, and in both cases, a consistent increase in the slopes of linear regression models, predicting SSC from discharge, was interpreted to indicate an increase in the availability of sediment for fluvial transport: a fixed increment in discharge yielded progressively greater increments in SSC.

The time series was subdivided into four successive intervals of equal duration (Table III). An AR1-ML model (Equation 5), with $\log_{10} Q$ as the only independent variable, was estimated for each interval; this model was selected as it is simple, and therefore amenable to interpretation, but capable of providing a good fit to the observed data. An AR1-ML model has two coefficients to which physical signifance may potentially be ascribed: the discharge and autoregressive terms. It was felt that estimating a diurnal component would not be a useful exercise in this case, as dummy diurnal variables are simply linear corrections estimated from the observed data; furthermore, it is already known that diurnal discharge–SSC hysteresis occurs in each subperiod (Hodgkins, 1996), and since fewer observations from given daily hours are available from the shorter dataset of each subperiod, the possibility of sampling bias is increased. The results are given in Table III.

The pattern in the AR1-ML models to some extent resembles that reported by Gurnell *et al.* (1994) and Hodgkins (1996), in that the coefficients (slopes) of $\log_{10} Q$ are not significant (at $p = 0{\cdot}05$) in the first two intervals, but are in the second two, of which the fourth slope is steeper than the third (Table III). The autoregressive coefficients are significant in all intervals, and decline throughout the season, but very slowly. More significantly, the T-statistics show that the autoregressive component enters far more strongly into the regression relationship than discharge, in all cases. The stochastic component of the model is therefore overwhelmingly responsible for generating the observed series. A clear pattern is established, of an important, relatively constant stochastic dependence on antecedent values of SSC, and a weak, highly changeable dependence on current values of discharge.

Gurnell *et al* (1994) estimated ARIMA models for six largely meteorologically defined subperiods of an SSC time series obtained from Austre Brøggerbreen, Svalbard, in 1992. Five of the models were of the form (1, 0, 0), i.e. first-order autoregressive models; the other was (0, 0, 0). A diurnal pattern in five of the subperiods was largely accommodated by differencing at the diurnal interval. An ARIMA (1, 0, 0) (0, 1, 0) model which generally described suspended-sediment transfer throughout the melt season at Austre Brøggerbreen is conceptually very similar to a regression model incorporating dummy diurnal variables, to remove autocorrelation arising from diurnal hysteresis, and a first-order autoregressive component, to remove true-autocorrelation among the residuals, i.e. Equation 6, which satisfactorily describes suspended-sediment transfer at Scott Turnerbreen. In both cases there is apparently little change in the form of the model throughout the melt season.

DISCUSSION

This paper's aims have been: first, to identify what forms of regression model most successfully account for variance in an SSC time series from the proglacial stream of a High Arctic glacier, and second, to infer physical controls on the variation in SSC, from interpretation of the parameters of models best capable of describing the series. Simple regression models are unsatisfactory statistical tools for the description and prediction of fluvial suspended-sediment transport, yet they became popular for such purposes, because of their ease of construction and interpretation. Improved methods such as ARIMA modelling and spectral analysis have yet to be applied widely to glacierized catchments, probably because they demand uninterrupted series of densely sampled observations, which are even now infrequently obtained. Hence it is useful to test methods which combines the flexibility and accessibility of linear regression with the rigour of time-series techniques. The following discussion refers to log-transformed data.

A bivariate linear regression model estimated for the 1992 Scott Turnerbreen SSC time series, deterministically estimating SSC from discharge alone, can account for less than 15 per cent of the variance in SSC, with a mean error of 54 per cent. Incorporating additional variables, representing

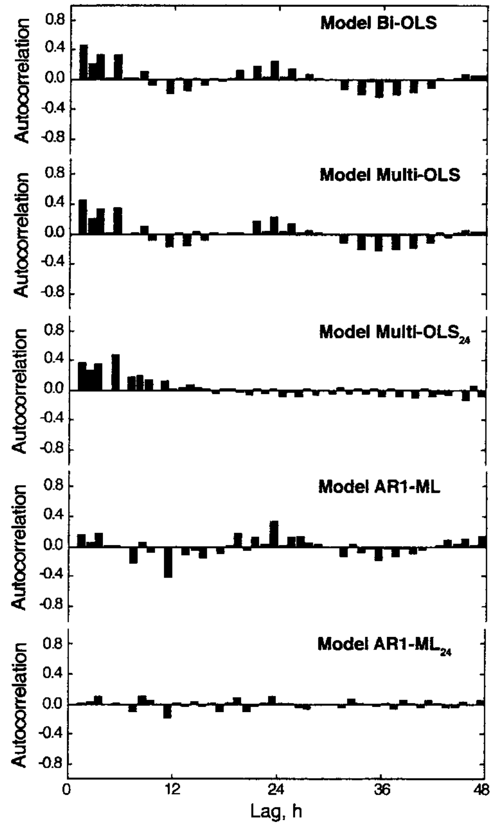

Figure 10. Autocorrelation functions from the suspended-sediment transfer models

Table III. Seasonal evolution of the coefficients of deterministic-stochastic, AR1-ML, SSC models (of the form $\log_{10}SSC_t = \varepsilon_t + a\log_{10}SSC_{t-1} + b\log_{10}Q_t + k$) derived for successive seven-day intervals. Italicized parameters are not significant ($p = 0.05$)

Interval	Constant *k*	*T*	*p*	Slope *b*	*T*	p	AR1 a	*T*	*p*	*n*
21–27 Jul	*0.078*	*0.821*	0.416	*0.306*	*1.584*	0.120	0.904	31.93	0.000	47
28 Jul–3 Aug	0.127	2.288	0.026	*0.080*	*0.537*	0.594	0.887	28.09	0.000	53
4–10 Aug	0.435	3.788	0.000	1.222	4.240	0.000	0.879	30.38	0.000	63
11–17 Aug	3.331	4.087	0.000	7.034	4.234	0.000	0.875	25.12	0.000	37

differing sediment supply processes (such as the rate of change of discharge and length of time since the current discharge was equalled or exceeded) into a multivariate model affords only a very modest improvement over the bivariate model. Autocorrelation in the residual series arises from two sources: diurnal hysteresis (quasi-autocorrelation) and the internal dependence of the series on itself (true-autocorrelation). Hysteresis at diurnal lags could be accounted for by diurnal differencing when a continuous series is available, but is here accommodated by the introduction of dummy diurnal variables. A diurnal multivariate regression model accounts for over 42 per cent of the variance in SSC, with a mean error of 13 per cent. True-autocorrelation can be almost entirely explained by incorporating an ARIMA (1, 0, 0) process into the regression model. T-statistics show that this process, combining

previous values of SSC with a current, random component, has an order of magnitude more explanatory power than current discharge. The best model achieved combines dummy diurnal variables and an autoregressive process into a multivariate model, with a mean error of 6 per cent. Moreover, the residual series resembles white noise, the residuals appear to be homoscedastically distributed with respect to predicted values of SSC, discharge and daily hour, and the autocorrelation function is apparently without pattern. The root mean square (RMS) error is halved during the model-building process (Table II).

OLS linear regression models of successive subperiods of the 1992 Scott Turnerbreen SSC time series, using proglacial discharge as the only independent variable, indicate that this variable accounts for between none (when the slope term is not significant) and over 52 per cent of the variance in SSC, and that the slope of the regression, when significant, increases during the melt season (Hodgkins, 1996). However, ML autoregression models, incorporating both discharge and an ARIMA (1, 0, 0) component, indicate that the latter dominates the regression relationship, and is relatively constant with a value close to unity, throughout the melt season. Likewise, Gurnell *et al.* (1994) found that a first-order autoregressive ARIMA model was largely sufficient to describe an SSC time series recorded at Austre Brøggerbreen, whereas a second-order autoregressive, or sometimes also a diurnal moving-average, model was required for SSC time series recorded at the temperate Haut Glacier d'Arolla in the Swiss Alps.

For both Svalbard glaciers, the stochastic processes generating the SSC time series are rather simple. An ARIMA (1,0,0) or first-order, autoregressive process, $SSC_t = \phi SSC_{t-1} + \varepsilon_t$, indicates a strong dependence of current values of SSC on previous values of SSC, i.e. suspended-sediment transfer is largely dominated by short-term sediment availability, a parameter which is well represented by recent values of SSC. Further, the simple generating process implies a simple drainage system structure. It must be unlikely that sediment supply, entrainment and transport processes are mediated through a complex drainage system if they yield a simply generated proglacial SSC series. This is consistent with other evidence for subaerial drainage through a single, short residence-time reservoir at these Svalbard glaciers (Hodgkins, 1998). Moreover, the SSC-generating process is relatively constant during the melt season at both Svalbard glaciers, despite increasing sediment supplies (Gurnell *et al.*, 1994; Hodgkins, 1996). This implies a relatively unchanging drainage system structure, as it must be unlikely that the SSC series could be represented by similar models under significantly different drainage configurations. There is a clear contrast with Haut Glacier d'Arolla: SSC series from that glacier require higher-order autoregressive or, at diurnal lags, moving-average models. Haut Glacier d'Arolla is a temperate glacier with a seasonally evolving, multireservoired, subglacial drainage network (Gurnell *et al.*, 1992; Sharp *et al.*, 1993).

CONCLUSIONS

The conclusions of this analysis of an SSC time series from the proglacial stream of a High Arctic glacier may be summarized as follows.

1. Though simple OLS linear regression models are generally unsatisfactory tools for the analysis of SSC time series, they are susceptible to modifications which significantly increase their descriptive, predictive and interpretative capabilities.
2. A bivariate OLS linear regression model, deterministically predicting SSC from discharge, explained less than 15 per cent of the variance in SSC. A multivariate model incorporating discharge, the rate of change of discharge and the length of time since discharge was equalled or exceeded as independent variables, offered little improvement over the bivariate model.
3. Diurnal hysteresis in the data gives rise to quasi-autocorrelation in the residual series from simple linear regression models. This was effectively removed by incorporating dummy diurnal variables, as hourly linear corrections to the slope of the discharge term, into the mutivariate model. This technique requires no assumptions to be made about the data, and applies across periods of apparently different response.

4. The presence of a first-order autoregressive, stochastic process gives rise to true autocorrelation in the residual series from simple and diurnal linear regression models. This was accommodated by incorporating an ARIMA (1, 0, 0) term into a multivariate autoregression model. Such a model requires estimation by a maximum-likelihood (ML), rather than an ordinary least-squares (OLS), method.
5. The process of building regression models, from a bivariate OLS model to a multivariate ML model incorporating dummy diurnal variables and a stochastic term, yielded a systematic progression in the explanation of variance in SSC, stripping away pattern in the residual series until its autocorrelation function was apparently left in the form of white noise. Model error is reduced from 54 per cent to 6 per cent, and RMS error (log-transformed data) from 0·260 to 0·134.
6. The dependence of SSC on the magnitude of discharge is weak and highly variable, whereas the dependence of current SSC on recent values of SSC, revealed through the stochastic term, is strong (an order of magnitude greater than discharge) and relatively constant. The dominant control on SSC is therefore short-term sediment availability. The simple and largely unchanging stochastic process generally responsible for generating the observed SSC series implies a simple and unchanging glacier drainage system.
7. A corollary of the conclusion that short-term sediment availability is the dominant control on SSC is that forecasting becomes problematic in the absence of recent SSC data. The challenge is therefore presented of identifying and modelling processes that control sediment availability.

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